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Top Level User Specifications for Mask Inspection Microscope

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Top Level User Specifications

for

Mask Inspection Microscope

Milestone 1 for
AIM Design Study

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User requirements

This document compiles top-level user specifications for an EUV microscope for characterizing EUVL mask defects. Two broad categories of application are considered: 1) emulation of the imaging characteristics of a stepper for printability analysis (*AIM mode*); and 2) high-resolution imaging for obtaining a more detailed characterization of defects or mask features. It is generally assumed that the mask defects that are to be characterized have been located by a previous inspection procedure and the spatial coordinates of the defect can be transferred to the microscope.[1]

Aerial Image Microscope (AIM) mode

In this mode the microscope is designed to emulate the illumination and imaging characteristics of a stepper to enable rapid evaluation of mask defects without the need for a resist exposure step. In this mode the main uses of the microscope would be:

- Review of multilayer and pattern defects to determine their printability
- Defect review following a repair process to assess the success of the operation
- Investigation of the effects of illumination and NA on the printed image
- Process window analysis of defects and other mask features

High-resolution mode

This imaging mode is designed to obtain the highest possible resolution on the mask for the purposes of understanding and characterizing defects on both unpatterned (i.e. blanks) and patterned masks. Potential uses for this imaging mode include:

- Assessing the sensitivity of printability to numerical aperture
- Gaining sufficient information to associate defects with particular processes, such as multilayer deposition or patterning
- High-resolution data for repair of features that do not clearly appear in AIM mode (for example OPC features)

It would be advantageous to identify a system design for the microscope that could accommodate both AIM and high-resolution imaging modes. This would enable the user to review a defect with effectively two lens objectives while not moving the mask or needing to reset the coordinate systems.

1 Top-level specifications

The heart of this document is a table of specifications for the proposed actinic mask inspection microscope. The AIM and high-resolution modes are considered separately, as both of these tools have nominally different optical systems. In many cases, the specifications for the two modes are identical, and suggest that a common platform might be adopted to address both intended uses. However, as this document does not constitute a design study, it would be premature to draw any conclusions with regard to the nature of the imaging system optics or magnification stages without that additional analysis.

We also distinguish between lithography nodes as appropriate, as we do not want to assume that the technology will remain the same for all nodes - there may be successive generations of EUV stepper and AIM-mode microscopes.

A commercial mask inspection microscope with an AIM mode capability is marketed by Carl Zeiss for optical lithography. Information on the specifications of the current commercially-available 193nm mask inspection microscope from Zeiss is also included, where available from catalog information, for the purposes of comparison and critical review.

The table is split into sections according to the nature of the data as follows:

Fixed specifications: Technology-related specification values that are neither flexible nor reviewable in development of an AIM-mode instrument. For example, the wavelength of operation, NA of the stepper, reticle format and mask feature sizes are specifications defining EUVL lithography technology to which the AIM-mode instrument must conform and is not flexible. However, the values set for these specifications are subject to adjustment pending the final specifications of production exposure tools.

[1] We will use the word "inspection" to refer to an initial measurement procedure performed prior to using this proposed microscope. Inspection rapidly identifies if "light point defects" are present and provides their coordinates for more detailed measurements on other instruments. This microscope will perform the functions referred to as "defect review" or "defect characterization".

Dependent specifications: AIM-mode specification values which result from the fixed specifications of EUVL technology, as defined above. For example the NA of the stepper defines the NA of an AIM-mode instrument, the pupil fill defines the required pupil fills on an AIM tool, and the mask feature size determines the spatial resolution required on the mask. Some of these specifications, for example NA in AIM-mode, are fixed while others, such as the NA in high-resolution mode, are flexible.

Integration specifications: Specifications that are largely dependent on the preferences of the end user. For example a unit must be compatible with a particular mask shop's cleanroom environments, but the specification for cleanliness may vary from company to company or even application to application within a company. While we suggest using data analysis software compatible with existing commercial AIM-mode instruments, this need not necessarily be the case. Often the specifications of this nature are a collaborative negotiation between the use and the instrument maker.

EUV mask inspection microscope
Top-level specifications

	Zeiss MSM-193	EUV Actinic Lithography Emulation (AIM) microscope		EUV high-resolution microscope
	130nm node	45nm node	32nm node	
Fixed specifications Stepper technology	5x DUV optical reduction steppers Transmissive masks Telecentric imaging through system	5x EUV optical reduction MET 0.3NA system (0.06NA to mask) 4x EUV optical reduction steppers Illumination 5-7° off normal at mask Imaging telecentric at wafer		
	0.7NA projector (0.14NA to mask)	0.25NA projection (0.063NA to mask)	0.25-0.30NA projection (0.-63-0.075NA to mask)	
Additional tool capacity		4x reduction ETS at 0.1NA (0.025NA to mask)		
Wavelength	193nm ArF laser	13.4nm 2% FWHM bandwidth		Same as for EUV AIM-mode system
Reticle format	6" square Protective pellicle	6" square multilayer coated Low Thermal Expansion Material (LTEM) per SEMI P37 specification		Same as for EUV AIM-mode system
Mask feature size	650nm	180nm (nominal) at 45nm node 128nm (nominal) at 32nm node 52nm isolated lines (13nm on wafer)		Same as for EUV AIM-mode system
Dependent specifications				
Resolution limit $\delta = \frac{\lambda}{2NA}$	0.1µm resolution in mask plane claimed 0.2NA optics diffraction limited to 480nm	108nm at 0.063NA	89nm at 0.075NA	27nm at 0.25NA 15nm at 0.45NA

	Zeiss MSM-193 130nm node	EUV Actinic Lithography Emulation (AIM) microscope		EUV high-resolution microscope
		45nm node	32nm node	
Corresponding pixel size $\delta/2$	45nm	54nm at 0.063NA	44nm at 0.075NA	13.4nm at 0.25NA 7.5nm at 0.45NA
		Specified pixel size depends on requirements for over-sampling		
Imaging system	20x 0.2NA Ultrafluar objective	Diffraction limited Variable NA to 0.063 (45nm node) 0.075 (35nm node) Wavefront error <λ/14 Specs TBD for coma, astigmatism, and distortion Flare similar to a stepper system or capability to simulate in software Working distance of 0.5-1mm		Diffraction limited 0.25-0.45NA high resolution system Wavefront error <λ/14 Working distance of 0.5-1mm
Imaging modes	Primarily stepper emulation mode	Brightfield through focus		Brightfield through focus Possibly also other modes - Dark-field - Phase-contrast / phase retrieval
Magnification Field of view (assuming 1000x1000 array of 20μm pixels)	150x 50x50μm field of view	>370x (approx) 54x54μm max	>450x (approx) 44x44μm max	1500x (approx) at 0.25NA 13.4x13.4μm max field at 0.25NA 2700x (approx) at 0.45NA 7.5x7.5μm max field at 0.45NA
		Required magnification depends on final sampling req'ts		
Telecentricity	Telecentric in transmission	Illumination at ~6° angle of incidence Image formed at ~6° angle from mask		Illumination and imaging angles flexible
Illumination	σ= 0.3-1 variable pupil fill Custom fills possible with using apertures in condenser	σ able to be varied by user Capacity for custom pupil fills		Need not match illumination of stepper Restricted σ in high resolution mode likely
Source	ArF Excimer laser at 193nm	Laser produced plasma or discharge source Power req't TBD		Same as for EUV AIM-mode system

	Zeiss MSM-193	EUV Actinic Lithography Emulation (AIM) microscope		EUV high-resolution microscope
	130nm node	45nm node	32nm node	
Focus control	25mm range in 0.05μm increments	Sub process-window resolution essential 25nm or better suggested Coarse, low resolution focus control may be required for loading the mask		Same as for EUV AIM-mode system
Dose control		Within 1% nominal dose		
Optical environment	Optics in air	Optics must be in vacuum Environmental monitoring system req'd		
Integration specifications				
Visual inspection mode	Available	Visible light imaging mode useful for preliminary alignment and evaluation		Same as for AIM-mode system
Stage (xy)	Stage calibrated using fiducials on mask	0.08μm resolution, repeatable Automatic calibration for cross-registration with other tools required.		Same as for AIM-mode system
Location and positioning	Import co-ordinate data from inspection tools for registration of defects Capacity for visible-light alignment	Must be able to import data from inspection tools.		Same as for AIM-mode system
Analysis software	AIMS image processing software licensed from IBM	Software interface should have similar functionality to the existing AIMS software from IBM. Licensing existing software is one option.		Same as for AIM-mode system
Tool environment	Class 10 cleanroom suggested	Unit must be compatible with mask shop environment (Class 10 cleanroom?) Load lock for masks makes sense (technology exists - SEM style)		Same as for AIM-mode system
Mask handling	Manual handling Masks loaded by hand directly onto stage	Vacuum environment will require either - some form of robotic load-lock, or - long pumpdown times between runs Must not add any defects to the mask SMIF pod interface, no agreement on type		Same as for AIM-mode system
Throughput	Individual images limited by CCD speed Overall throughput limited by stages and	Approx 5 mins to load mask via load-lock Imaging limited by data capture rate		

	Zeiss MSM-193 130nm node	EUV Actinic Lithography Emulation (AIM) microscope 45nm node	 32nm node	EUV high-resolution microscope
	loading time			
Vibration specs	<2μm amplitude in range 0.1-100Hz	Will depend on system mechanics		
Ergonomic format	Bench-top computer-controlled microscope Can use eyepieces for visible inspection	Benchtop footprint with compact source may resemble SEM		
System control	Integrated controller	PC interface for overall system control Subsystems transparent to user with single integrated controller for all non-imaging functions		
Physical size	1.8 x 1 x 1.8m footprint (LxWxH) 2 x 1.3 x 1.8m floorspace 200kg, 500VA power consumption	To be determined (system dependent) Less than 2x2x2m all up including source		

2 Notes on the specifications

2.1 Target node

Entry of EUV technology is currently anticipated at the 45nm node, however the technology is scalable to the 32nm node and beyond. It therefore makes sense to similarly target any AIM tool at the 45nm node with technology scalable to 32nm and beyond if possible. It might be desired for an instrument to immediately target the 32nm node, since Sematech will install the 0.3NA MET in 2004, and be able to image defects consistent with the 32nm node. It might also be desireable for the AIM mode instrument to operate with an NA compatible with the ETS, which would be 0.1/4 = 0.025. For MET, 0.3NA/5=0.60.

2.2 Spatial resolution

The incoherent resolution limit of an optical system is at $k_1 = 0.5$, thus the smallest feature size we expect to resolve at a given NA is at $\delta = \lambda/2NA$. To adequately sample this image we must use a detector with sufficient resolution to sample at or above the Nyquist frequency, pixel spacing, which refers to the center point of the photosensitive element, must be $\Delta x = \delta/2$ or smaller. This assumes perfect idealized pixels, but the CCD pixels themselves also contribute to the total transfer function of the system. Thus, in practice, it is necessary to oversample the image by some factor so as to ensure accurate image measurement. As the design process proceeds, the required level of oversampling should be reconsidered and pixel spacing will likely take a value between $\delta/4$ and $\delta/2$. Assuming for the moment detection at the Nyquist frequency of $\Delta x = \delta/2$ or smaller the maximum spatial resolution and corresponding pixel sizes are thus as follows:

Mode	NA	Resolution limit $\delta = \frac{\lambda}{2NA}$	Pixel size at mask $\Delta x = \frac{\delta}{2} = \frac{\lambda}{4NA}$
Actinic stepper simulation Mode	0.25NA at 4x = 0.0625NA 0.3NA at 4x = 0.075NA	108nm 89nm	54nm 44nm
High resolution mode	0.25NA 0.45NA	27nm 15nm	13.4nm 7.5nm

To emulate a 0.25NA stepper with a reduction factor of 4x the mask-side pupil is at 0.0625NA, thus the spatial resolution of the stepper on the mask is δ=108nm. 54nm pixels are therefore required to adequately sample the image.

Operating at 0.45NA in high resolution mode much smaller pixels are required: at 0.45NA δ=15nm thus necessitating 7.5nm pixels at the mask to fully take advantage of the higher resolution.

It is important to consider that oversampling the image may be advantageous in minimizing OTF roll-off. Therefore the desired pixel sizes may up to 2x smaller.

2.3 Detector specifications

Detector specifications are system dependent and are not considered in this section. The detector will vary depending on the optical system configuration and could take the format of a CCD, photocathode, image plate, or other system. For the sake of convenience we have assumed a 1000x1000 array of 20μm pixels as a baseline reference in this document.

2.4 Optical system

Feedback from industry is that the optical resolution should not be compromised. Aim for a higher magnification and smaller pixel size than available on current tools (relative to mask feature size) if possible.

2.4.1 Numerical aperture (stepper emulation mode)

The imaging system must have an NA equal to or greater than the input NA of the stepper so as to be able to accurately simulate the stepper imaging performance. Systems with smaller NA than the objective can be emulated by inserting apertures into the system thus it is prudent to err on the side of higher NA if possible. To be compatible with a 0.3NA 4x reduction stepper system for use at the 32nm node therefore requires a mask-side NA of 0.075.

Stepper NA	Mask-side NA
0.25NA stepper at 4x reduction	0.0625
0.3NA stepper at 4x reduction	0.075

0.3NA MET at 5x reduction	0.06
0.1NA ETS tool at 4x reduction	0.025

2.4.2 Numerical aperture (high resolution mode)

For higher resolution imaging it is necessary to go to a higher NA optical system. As the system does not have to emulate the NA of a stepper there is some choice in the selection of NA, subject to the limitations of particular system configurations.

One potential use of an AIM system is for the classification of phase and amplitude defects. For this application calculations indicate that the numerical aperture required to distinguish between phase and amplitude defects of height is of the form $a < wNA/1.72$ where a is the height of the bump and w its Gaussian radius on the mask. Not all defects can be repaired, and preliminary calculations indicate that that an NA of at least 0.2 should be adequate to cover repairable defects.

2.4.3 Telecentricity

Whilst DUV systems are telecentric, in an EUV system the reflective mask is illuminated at ~6 degrees and the reflected light is collected at the same angle but on the opposite side of the normal. This places some limitation on the available ranges of mask side NA if the imaging optics are not to occlude the illumination beam. For the incoming beam not to occlude the outgoing beam, we need $\theta_1+\theta_2<12$ degrees, where $\sin(\theta_1) = \sigma*NA$ and $\sin(\theta_2)=NA$. For $\sigma=1$, this means the maximum NA is equal to sin(6 degrees) = 0.104.

Illumination at 6 degrees also causes a lateral image shift as the stage is moved through focus. This can be compensated for by either translating the stage as focus is changed, or by making the imaging system telecentric at the detector and defocusing the detector rather than the mask. To avoid image processing and overlay problems the latter approach would be preferable, but is dependent on system design.

2.4.4 Working distance

The current AIM tool has a working distance of 7.4mm to accommodate masks with protective pellicles. There is no suggestion that EUV masks will be protected by pellicles of this thickness so there is no need to maintain this requirement for an EUV system. In the absence of a pellicle the minimum working distance is set by practical considerations such as mask mounting and positioning error. To provide some margin of error in positioning the stage and objective to minimize the danger of damaging the mask. The working distance available on current metallurgical objectives for visible light microscopes is of the order of 0.5 to 1mm, and this would appear to be a reasonable starting figure for an EUV tool.

2.4.5 Magnification

The required magnification will depend on the type of detector used and is therefore not a fixed value. Potential detectors include, but are not limited to, a CCD, image plate, photocathode or scintillator, all of which have different effective pixel sizes and therefore different required magnifications.

Working for the moment on assumption that the final detector will be a CCD with 20μm pixels the required magnification can be computed from the ratio of the desired pixel size in the mask plane to the size of the CCD pixels in the image plane. For a detector with a 20μm pixel size this gives a total system magnification of 370x if we operate only in AIM mode, but a magnification of 2700x if we also include a 0.45NA high-resolution mode.

2.4.6 Field of view

The useful field of view is determined by either distortion and aberrations across the field in the optical system or by the number of pixels in the detector. Optical effects depend on a combination of lens design and the final system configuration selected, whilst in a scanning system the number of pixels is effectively unlimited thus there is no effective upper bound to the field of view other than the time taken to acquire the image.

To provide some estimate of the field size a discussion is presented based on the number of pixels in the detector. Typical CCD array sizes are of the order of 1000x1000 pixels, which gives maximum a field of view given by the pixel resolution on the mask times the number of pixels. If we operate with a system that is only capable of operating in AIM mode with 54nm pixels we will have a field of view of 54μm, whilst if we construct a high-resolution 0.45NA system and stop it down for operation in AIM mode we will have a field of view of only 7.5μm even in AIM mode. Note that this is the field of view for a single CCD exposure – multiple exposures can be stitched together in software to create a virtual field much larger than this size.

2.5 Illumination

2.5.1 AIM mode

To properly emulate the function of a stepper it is essential to have the capacity to emulate the pupil fill of a production system. Pupil fills may vary amongst manufacturers and with machine generation, thus it is essential not to tie the illumination system to one particular optical system. Some capacity to produce custom fills is essential, and could be achieved either by the use of apertures in the illuminator or by a scanning mirror that paints out a pupil fill during the course of an exposure.

2.5.2 *High resolution mode*

For highest spatial resolution it is best to use a large pupil fill. However, the EUV the reflectivity of a multilayer is strongly dependent on the angle of incidence thus full pupil fill may not be practical when operating the microscope in high resolution 'microscope' mode. Furthermore because an EUV system operates in reflection rather than transmission it may not be possible to obtain full pupil fill in high-resolution mode because the obscuration caused by the optical elements themselves may provide some limitation on the range of available pupil fills.

Some of these constraints will be imposed by the particular imaging systems that restrict the range of available apertures. The proper place to consider these is in relation to the individual imaging systems, so discussion of available pupil fills for high-resolution mode is deferred to the system-level discussion. Some consideration also must be given to the use of either critical or Köhler illumination modes.

2.6 Stage travel (x-y)

Keeping the ratio of mask feature size to stage resolution consistent with that on current AIM tools gives a required stage resolution in the EUV of 0.08μm. This is the same as the optical spatial resolution of is 0.08μm obtained when emulating a 4x 0.3NA stepper (0.075NA to the mask). In high resolution mode the field size is of the order of 7.5x7.5μm, and a stage of this accuracy should enable positioning of the mask to sufficient accuracy that the desired feature will be well placed within the field of view to within 10 pixels.

A repeatable positioning resolution of 80nm is only slightly more than 1/6 of a wavelength at 500nm and so should be well within the resolution of interferometric optical encoders. The stage co-ordinates must also be able to be calibrated with regard to fiducials on the mask for the purposes of cross-registration with other tools, and must be done automatically and transparently to the user in software. A system similar to that in use on current AIMS tools would suffice.

2.7 Focus control

It is essential that the focus control have better resolution than the process window of a stepper. The mask flatness spec is 50nm, and to sample this adequately it would be necessary to have 25nm focus resolution. Capacity to resolve a factor of 2-5 better than the mask flatness spec may be desirable for some high-precision analysis modes.

Note that a leverage factor of the magnification squared can be obtained by defocusing the detector rather than the mask. There could be significant advantage to this approach: not only does it provide a ready method for obtaining fine focus control, but it also eliminates image shifts as the focus is changed if the imaging system is made telecentric at the detector. It is also worth pointing out that focus control can be separate from the mechanics of moving the mask in the Z-direction. Piezoelectric actuators are ideally suited to the fine focus resolution required for probing the process window, whilst a coarser system would be adequate for moving the mask into the focus range of the microscope.

2.8 Throughput

The desired throughput is to a certain extent user-defined. On current tools a good operator can cycle a mask (set up, align, image, remove) about one mask per half an hour, with 5 minutes per exposure (find, focus, capture, etc.). Similar or better turnaround time should be targeted for on an EUV inspection tool, although this spec will have to be refined in consultation with potential users given the application in mind.

There are two fundamental limiting factors on throughput: data capture rate and loading rate. The need for a vacuum environment for EUV will make the system slower to load than current systems that operate in air. As a guide, on current SEMs it takes 5 minutes to load a 6" wafer down to a vacuum of approx 10^{-11} Torr operating pressure. EUV optics don't require such a high vacuum so this would be a reasonable upper bound on the desired loading rate. Total mask throughput would then be governed by how fast a mask can be loaded and focussed, and to a certain extent by stage speed (for example the need for calibration and accurate registration). A 5 minute vacuum load is not inconsistent with current thoughput rates and could be made a negligible limiting factor with some automation of the system (for example by imaging one mask while pumping down the next).

The data capture rate is limited by either the CCD imaging speed (data download rate) or source power (getting enough photons onto the CCD). Data processing can be solved with faster computers, whilst good system integration should mean that little time is spent configuring the machine. Ideally, an EUV tool should be data rate rather than source limited; a high-resolution scientific grade CCD takes a few seconds to download an entire image, so individual frame exposure times of less than a second should be aimed for.

2.9 Environment

Current AIM tools suggest a class-10 cleanroom environment and are compatible with the cleanroom environment of a mask shop. Similarly an EUV tool will also have to be compatible with mask shop cleanrooms, although the use of SMIF loading pods and robotic handling may mean that only the loading area and inside of the tool need be within the cleanroom. The cleanliness requirement is an issue to be determined between the supplier and customer.

There is, however, some difference in the optics and the requirement to use a vacuum for EUV. 193nm optics can work in an air environment whilst EUV optics must be housed in vacuum because the absorption length of 13.5nm light in air is less than the optical path in the imaging system. This means that specifications are required for cleanliness of the vacuum environment. This should be as clean as the mask area of a production stepper so as to minimize the number of defects added.